

# **NASA Technical Memorandum 89057**

## **DESCRIPTION OF THE SPACECRAFT CONTROL LABORATORY EXPERIMENT (SCOLE) FACILITY**

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SPACECRAFT CONTROL LABORATORY EXPERIMENT  
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## SUMMARY

The Spacecraft Control Laboratory Experiment is a facility for the investigation of control techniques for large flexible spacecraft. The control problems to be studied are slewing maneuvers and pointing operations. The facility implements the salient characteristics of a flexible satellite with distributed sensors and actuators.

The flexible satellite is represented by a continuous structure consisting of a large mass and inertia connected to a small mass and inertia by a slender, flexible beam. The structure is suspended by a single cable mounted to a universal joint at the system C. G. The sensors for the experiment consist of aircraft quality rate sensors and servo-accelerometers. The shuttle attitude will be determined through a combination of inertial measurements and optical sensing techniques. Actuators for the experiment consist of Control Moment Gyros, reaction wheels, and cold gas thrusters. Computational facilities consist of micro-computer-based central processing units with appropriate analog interfaces for implementation of the primary control system, the attitude estimation algorithm and the CMG steering law. Details of the experimental apparatus and the system software are presented in this paper.

## ABSTRACT

A laboratory facility for the study of control laws for large flexible spacecraft is described in the following paper. The facility fulfills the requirements of the Spacecraft Control Laboratory Experiment (SCOLE) design challenge for a laboratory experiment, which will allow slew maneuvers and pointing operations. The structural apparatus is described in detail sufficient for modelling purposes. The sensor and actuator types and characteristics are described so that identification and control algorithms may be designed. The control implementation computer and real-time subroutines are also described.

## INTRODUCTION

A modelling and control design challenge for flexible space structures has been presented to the technical community by the NASA and IEEE (ref. 1). The Spacecraft Control Laboratory Experiment (SCOLE) was constructed to provide a physical test bed for the investigation and validation techniques developed in response to the design challenge. The control problems to be studied are slewing maneuvers and pointing operations. The slew is defined as minimum time maneuver to bring the antenna line-of-sight (LOS) pointing to within an error limit of the pointing target. The second control objective is to rotate about the line of sight and stabilize about the new attitude while keeping the LOS error within the bound  $\delta$ . The SCOLE problem is defined as two design challenges. The first challenge is to design control laws, using a given set of sensors and actuators, for a mathematical model of a large antenna attached to the space shuttle by a long flexible mast. The second challenge is to design and implement the control laws on a structural model of the system in a laboratory environment. This report gives preliminary specifications of the laboratory apparatus so that interested investigators may begin design and simulation for the laboratory experiment.

The laboratory experiment shown in figure 1 attempts to implement the definition of the modelling and control design challenge within reasonable limits of the 1-g atmospheric environment. The experimental facility exhibits the essential SCOLE characteristics of a large mass/inertia (space shuttle model) connected to a

small mass/inertia (antennae reflector) by a flexible beam. Control sensors and actuators are typical of those which the control designer would have to deal with on an actual spacecraft. Some trades are made in terms of structure, sensors, actuators, and computational capability in order to develop the experiment in a timely and cost-effective manner. To this end, the basic structure is made of homogeneous, continuous elements. It is suspended from a steel cable with the positive z-axis of the shuttle pointing up, thus minimizing the static bending of the antenna mast. The suspension point is a two-degree-of-freedom gimbal for pitch and roll with yaw freedom supplied by the suspension cable. The sensors are aircraft quality rate sensors and servo-accelerometers. The shuttle attitude will be determined through a combination of inertial measurements and optical sensing techniques.

The shuttle control moments are provided by a pair of two-axis control moment gyros (CMG's). Mast-mounted control torques can be applied by a pair of two-axis reaction wheels. The reflector-based forces are provided by solenoid-actuated cold-air thrusters. Reflector mounted torque devices are a trio of high-authority reaction wheels. Computational facilities consist of micro-computer-based central processing units with appropriate analog interfaces for implementation of the primary control system, the attitude estimation algorithm, and the CMG steering law. All of the elements which make up the SCOLE experiment are described in detail in the following text.

The description of the apparatus covers five major groups: The basic structural elements are described and pertinent dimensions and structural properties are provided. The sensor locations and their dynamic properties are presented. The actuator locations and estimated dynamic properties are also given. The mass properties of the combined structure, sensor and actuator system are given. Finally, the computing system and analog interfaces are described.

The contents of this report are considered accurate at the time of publication. All of the planned SCOLE components are implemented and are available to the user at a raw signal level. However, due to continued refinement of some of the components, specific details of the system may change over the life-time of the experimental apparatus.

## STRUCTURES

The SCOLE is comprised of three basic structures, the shuttle, the mast, and the reflector panel. The assembly of these individual components and the global reference frame are shown in figure 2.

The shuttle planform is made from a 13/16-inch steel plate and has overall dimensions of 83.8 by 54.0 inches. Its total weight is 501.7 pounds. The shuttle's center-of-mass is located 3.4 inches below the experiment's point of suspension, and 26.8 inches forward of the tail edge (fig. 3).

The mast is 120 inches long. It is made from stainless steel tubing and weighs 4.48 pounds. One-inch thick manifolds are mounted to the mast at each end. The assembly of these parts and their dimensions are shown in figure 4.

The reflector panel is hexagonal in shape, made from welded aluminum tubing, and weighs 4.76 pounds (fig. 5). It is located 126.6 inches below the SCOLE's point of suspension. The center of the reflector is located at 12.0 inches in the x direction and 20.8 inches in the y direction from the end of the mast.

The complete system is suspended from an 11-foot cable attached at the system center-of-gravity via a universal joint. Roll and pitch rotational freedom is provided by pillow-block ball bearings which have an estimated break-out torque of 0.1 ft-lb. The universal joint is shown in figure 6. It is fixed to the shuttle plate, and the system center-of-gravity is made to coincide with the center-of-rotation by means of an adjustable counter balance system.

## **SENSORS**

The sensors for the experiment consists of nine servo-accelerometers and two, 3-axis rotational rate sensing units. An optical sensor will provide yaw attitude of the shuttle. The power supplies for these sensors are mounted on the shuttle plate to minimize the number of large gauge wires which must cross the universal joint suspension point. Only a single 115 VAC cable and 33 signal wires cross the universal joint. The wires for the sensors are routed on the shuttle and along the mast.

### **Accelerometers**

All nine accelerometers have a frequency response which is nearly flat up to 350 Hz. Linearity is within 0.17 percent of the full-scale output. A typical calibration is presented in figure 7. Individual calibrations are available on request.

The shuttle-mounted accelerometers shown in figure 8a sense the x, y, and z accelerations. These sensors are distributed away from the suspension point to aid inertial attitude estimation. The locations and sensitive axis are shown in figure 8b.

The mast-mounted accelerometers shown in figure 9a sense x and y acceleration at locations about one-third of the mast length from each end. The positions and sensing axis of the devices are shown in figure 9b.

The reflector-mounted accelerometers are shown in figure 10a. They are positioned in the center of the reflector below the thrusters and sense the x and y accelerations. The coordinates and sensing axis of the devices are shown in figure 10b.

### **Rate Sensors**

The rotational rate sensors are three-axis, aircraft-quality instruments. The frequency response is approximately flat to 1 Hz and -6 db at 10 Hz. Linearity is about 0.6 percent full scale. A typical calibration is shown in figure 11. The range is 60 deg/sec for the yaw and pitch axis and 360 deg/sec. for roll. The threshold is 0.01 deg/sec.

The shuttle-mounted rate sensor package, shown in figure 12a, senses three-axis, rigid body angular rates of the shuttle plate. Its coordinates and sensing axis are presented in figure 12b.

The mast-mounted rate sensor package, shown in figure 13a, senses three-axis angular rates at the reflector end of the mast. Its coordinates and sensing axis are presented in figure 13b.



The sensor information required for control system design is summarized in Table I. The sensor type is listed in column 2, and its sensed variable is listed in column 3. The analog interface channel is listed next. The coordinates of the parts with respect to the universal joint are listed in the next three columns. The sensitivities in terms of analog-to-digital converter units are listed next. The error list shows the RMS deviation of the rate sensors or the percentage of full-scale linearity error for the accelerometers. The linear range of the instruments is listed in the next-to-last column.

### OPTICAL SENSOR

An optical sensor will be provided to determine yaw attitude of the shuttle. The optical sensor is a planar photo-diode with appropriate optics mounted on the ground. The outputs of the sensor are proportional to the position of an infrared light source on the shuttle. The sensor data is processed by a dedicated micro-controller and then sent to the main CPU over a serial data link for transformation to attitude angles. No photographs or calibration data are available for this device.

### ACTUATORS

The actuators consist of both proportional and on-off controllers. Shuttle attitude control is provided by a pair of two-axis control moment gyros (CMG's). Mast vibration suppression can be achieved with a pair of orthogonally mounted reaction wheel actuators positioned at two stations on the mast. Reflector forces are provided by four cold gas jets. Reflector torques are provided by three orthogonally mounted reaction wheels at the end of the mast. As with the sensors, all devices are inertial, and the power supplies and amplifiers are mounted on the shuttle. Fifteen command signal wires cross the universal joint. All actuators were manufactured in house.

### Control Moment Gyros

The CMG's each have two gimbals which are equipped with individual direct drive DC torque motors. The momentum wheel is mounted in the inner gimbal and driven by two permanent magnet DC motors. The nominal operational momentum is about 2.5 ft-lb-sec. The gimbal torque motors are driven by current amplifiers so the output torque will be proportional to the command voltage sent to the amplifier. The gimbal torquers will produce  $\pm 1.5$  ft-lbs at frequencies up to 1kHz. The gimbals are instrumented with tachometers and sine-cosine potentiometers to facilitate decoupled control of the shuttle attitude angles. A dedicated computer will be used to control the CMG gimbals. Routines will be provided so that users may command decoupled shuttle torques or gimbal torque commands.

The sensitivity calibration curve of a typical gimbal motor is shown in figure 14. No other calibration data are available for the CMG's.

The forward CMG is shown in figure 15a. Note that the outer gimbal is fixed and parallel to the pitch axis of the shuttle. The inner gimbal is nominally oriented so that the spin axis of the momentum wheel is parallel to the shuttle z-axis. The second CMG is mounted at the rear of the shuttle so that the outer gimbal is

parallel to the z-axis. The inner gimbal is nominally oriented so that the rotor spin axis is parallel to the shuttle x-axis. The coordinates and nominal axis of actuation of the CMG's are shown in figure 15b.

### Reaction Wheels

The mast-mounted reaction wheels consist of aluminum disks with inertia of about  $0.00027 \text{ lb-ft-sec}^2$  mounted directly on the drive shaft of a 20 oz-in permanent magnet DC motor. The motors are powered by high bandwidth current amplifiers. A torque sensitivity plot is presented in figure 16. No other calibration data are available. A typical reaction wheel assembly is shown in figure 17a. The two actuator locations and their axis of actuation are shown in figure 17b.

The mast end mounted reaction wheels consist of D C permanent magnet pancake motors which are mounted with the armature fixed to the structure. The stator and case of the motor are allowed to rotate via a slip ring assembly, thus providing high inertia mass to fixed mass efficiency.

The motors are powered by high bandwidth current amplifiers. The torque capability of these devices is estimated to be about 50 oz-in. No sensity plot or other calibration data is presently available. The three-axis reaction wheel assembly is shown in figure 18a. The actuator locations and their axis of actuation are shown in figure 18a.

### Thrusters

The control forces on the reflector are provided by solenoid actuated cold gas jets. The thrusters are mounted in the center of the reflector and act in the x-y plane. The jets are supplied by a compressed air tank mounted on the shuttle. The pressurized air travels through the mast to the solenoid manifold, which gates the air flow between the regulated supply tank and the thrusters as shown in figure 19. Thrust is initiated by opening the solenoid with a discrete command. The rise time and transient oscillation of thrust is shown in figure 20. The magnitude and duration of the thrust before the air supply is depleted at 60-psi nozzle pressure is shown in figure 21. The pertinent data from figures 20 and 21 are tabulated in Table II.

The thrusters are shown in figure 22a. Their location and axis of actuation are shown in figure 22b.

The actuator information required for control system design is summarized in Table III. The actuator type and direction of action are listed in Column 2. The analog interface channels are listed in Column 3. The coordinates of the devices are listed in the next three columns. The sensitivities of the actuators in terms of digital-to-analog converter units are shown in Column 7. An estimate of the thruster RMS deviations exhibited in figure 19 is presented as error data. No other error data are available. The maximum range of the system actuators is shown in the next-to-last column.

## MASS PROPERTIES

The position and weight of the various pieces of equipment, which collectively form the SCOLE apparatus, are cataloged in Table IV. Distances are measured from the point of suspension to the approximate center-of-mass of each component. Each major component is listed in the second column of the table. The x, y, z coordinates are listed next. The weight of each component is listed in Column 6. The remaining columns are the mass moments and moments of inertia. The totals for the complete system are presented on the bottom row.

## COMPUTER SYSTEM

The main computer for control law implementation will be a micro-computer based on the Motorola M68000 microprocessor. The computer has 2.0 M-byte of random access memory and a 40 M-byte hard disk. The operating system is based on UNIX with C, Fortran and Pascal compilers available for applications programming. The computer has 12 serial ports and 1 parallel port. Terminals are connected on four of the ports and an answer-only modem is attached to another. One port is used for an originate-only modem. A line printer is attached to another port. The optical sensor is connected to a serial port. The IBM PC, which is used to drive the CMG's, is also connected to a serial port.

Analog interfaces consist of a four-bit, output-only discrete channel: an 8 bit discrete output port, an 8-bit discrete input port, 8 digital-to-analog converters, and 64 analog-to-digital converters. All converters are 12-bit devices with a range of  $\pm 10$ v. These interfaces are shown schematically in figure 23. The CMG control software required for the PC should be relatively transparent to the controls designer who will be operating on the CRDS computer.

Subroutines for accessing the analog interfaces and setting the digital sampling interval are described in Appendix A. The most commonly used routines are listed below.

For accessing the analog devices:

- getadc - read the analog-to-digital converters
- setdac - set the digital-to-analog converters
- thrust - set the cold-gas thrusters.

To control the sampling interval:

- rtime - sets the sample period marks the beginning of a real-time loop.

A time-line of the synchronization of the sample interval using the routine rtime and the analog interface routine usage is shown in figure 24. The basic operation is as follows:

The user first calls rtime with flag=.true., and a valid sample interval. After setting the timer period, the routine starts the user's real-time routine and the interval clock. The user routine will use some or all of the subroutine calls shown. When the user computations and actuator commands are complete, the routine must return to the top of the real-time loop and once again call rtime. If this occurs before the end of the sample interval, the time-out condition will be inhibited and rtime will wait for the next rising edge of the sample interval clock and then return

to the calling program. If the user computations take longer than the sample interval, a time-out condition will be signaled to the operator when `rtime` is called. The user may choose to ignore the condition and continue or may take specific steps to alleviate the condition.

The procedure for logging on to the computer is as follows:

Set communication parameters to 1200 baud, 7 bit, even parity.  
Dial in to the Langley data communication switching system at 804-865-4037. When connected, type a carriage return.  
To the system prompt "ENTER RESOURCE CODE" type "acrl."  
Wait until "GO" and the "name:" prompt appear on the screen.  
Type in your log-in information. All investigators will be given a three-letter log-in name (usually the university affiliation).

Some useful system commands are listed below:

To transfer a file to the experiment computer from a smart terminal, type `cat <filename> <cr>` and then enable the upload function of the local terminal. When the upload is complete, type `<ctrl>d`.

To transfer a file from the experiment computer to a smart terminal, type `cat <filename>` then enable the download function of the local terminal and type a `<cr>`.

To list the contents of a directory, type `l <cr>`.

To look at a file, type `p <filename>`.

To compile a FORTRAN program and link with real-time system commands and TCS graphics, type `frt <filename>`.

Note: `<filename>` must have the extension `.for`. The executable code will be under `<filename>` without the `.for` extension. To run, simply type `<filename>` without any extension.

To list the system commands, type `l /bin`. to get a description of any command, type `describe <command>`.

System user guides will be available upon request from the Spacecraft Control Branch, M/S 161, NASA Langley Research Center, Hampton, VA, 23665-5225. Other details for operating in a real-time mode will be provided at the time of implementation.

#### CONCLUDING REMARKS

The SCOLE laboratory facility is an experimental apparatus which permits ground-based investigation of identification and control algorithms for large space structures. The facility exhibits structural dynamics similar to those expected on the large satellites. The sensors and actuators are typical of those, which may be used on an operational satellite. The computational system is reasonably sized with current technology processors and permits ready access to the facility for interested investigators.

The description of the structural assembly, the sensor and actuator configuration, and software provided in this paper should be sufficient for SCOPE investigators to begin designing identification and control algorithms for the SCOPE facility.

## APPENDIX

### REAL-TIME SYSTEM SUBROUTINES

Analog I/O system command.

NAME:

**getadc** Samples the analog-to-digital converters.

COMMAND:

**getadc [-s]**

DESCRIPTION:

This command is used to sample the analog-to-digital converters and display selected channels at the terminal. The +/- 10.0 volt input range is scaled to +/- 1.0 units so a single bit is worth .00049 units. The channels to be displayed are selected with the -s option. This option displays a menu which allows the user to set the print flags for the individual ADC channels. Specific choices are:

- 1) turn on all print flags,
- 2) turn off all print flags,
- 3) turn on a range of print flags,
- 4) turn off a range of print flags,
- 5) display current print flags,
- 6) save current print flags.

If the command is executed without the -s option, the last set of print flags is used to selectively display the ADC channels.

USES:

**getadc.flags**

DIRECTORY:

**/bin**

SOURCE:

**/usr/csc/ele/getadc.c**

Analog I/O system command.

NAME:

**getadc** Samples the analog-to-digital converters.

COMMAND:

**getadc [-s]**

DESCRIPTION:

This command is used to sample the analog-to-digital converters and display selected channels at the terminal. The +/- 10.0 volt input range is scaled to +/- 1.0 units so a single bit is worth .00049 units. The channels to be displayed are selected with the -s option. This option displays a menu which allows the user to set the print flags for the individual ADC channels. Specific choices are:

- 1) turn on all print flags,
- 2) turn off all print flags,
- 3) turn on a range of print flags,
- 4) turn off a range of print flags,
- 5) display current print flags,
- 6) save current print flags.

If the command is executed without the -s option, the last set of print flags is used to selectively display the ADC channels.

USES:

**getadc.flags**

DIRECTORY:

**/bin**

SOURCE:

**/usr/csc/ele/getadc.c**

Analog I/O system command.

NAME:

**setdac** Sets the digital-to-analog converters.

COMMAND:

**setdac [-s] [-0]**

DESCRIPTION:

This command is used to set the voltage on a range of digital-to-analog output channels. The +/- 1.0 unit output range is scaled to +/- 10.0 volts so a single unit is worth .0049 volts. The channels to be set are selected by executing the command with the -s option. This option displays a request for the range of channels to be set, and then queries for individual channel values in terms of units. All DAC channels may be set to zero by executing the command with the "-0" option.

USES:

Nothing.

DIRECTORY:

/bin

SOURCE:

/usr/csc/ele/setdac.c



UNOS system command.

NAME:

lterm Terminal emulator.

COMMAND:

term [-s] [-S]

DESCRIPTION:

This command connects the user terminal to the Langley central data communication switch at 1200 baud. This is a dumb terminal emulator which provides rudimentary file transfer capabilities. No attempt is made to emulate control codes of any particular terminal for editing purposes.

The emulator commands are as follow:

- @ Return to UNOS (operating system.)
- ! To download a file.
- ^ To upload a file.
- To excute a system command.
- ? For help.

The options are:

- s 300 baud
- S 900 baud

Upload means to transfer a file from the Charles River computer to the remote computer. The remote computer must have some mechanism for receiving the text.

Download means to transfer a file from the remote computer to the Charles River computer. No attempt is made to check for existence of the receiving file name before saving the downloaded file.

USES:

/doc/cmds/lterm.help

DIRECTORY:

/bin

SOURCE:

/jpw/lterm.c

Analog I/O system command.

NAME:

8751\_test    Test the serial communication link to the 8751 boards.

COMMAND:

8751\_test

DESCRIPTION:

This command facilitates verification and calibration of the 8751 micro-controller interface over the RS-232 serial ports. The command queries for voltages to be output by the digital-to-analog converters on the 8751 boards. The data input is in terms of units with 2047 equal to 9.9951 volts and -2048 equal to -10.0000 volts. If the input line contains only one value, all active boards are sent that value. Otherwise, individual values are sent.

USES:

motint()  
motsub()

DIRECTORY:

/bin

SOURCE:

/usr/rdb/8751\_test.for

Analog I/O system subroutine.

NAME:

**getadc()** ( C callable ) Sample a range of analog-to-digital converters.

CALL:

```
int error, first_adc, last_adc;
float adc_data_pointer;
int getadc( first_adc, last_adc, &adc_data_pointer)
error = getadc(first_adc, last_adc, &adc_data_pointer)
```

DESCRIPTION:

This subroutine samples a range of analog-to-digital converters. The +/- 10.0 volt input range is scaled to +/- 1.0 units so a single bit is worth .00049 units. The arguments are:

**first\_adc** (int) First converter to be sampled (numbering starts from zero.)

**last\_adc** (int) Last converter to be sampled (maximum is 63.)

**&adc\_data\_pointer (\*)** Starting location for storing sample data. Data are floating point values with a range of +/- 1.0.

RETURNS:

**error = 0** indicates valid transfer.

**error =** indicates bad range.

USES:

Nothing

LIBRARY: None

SOURCE:

/usr/csc/ele/getadc\_c.c

Analog I/O system subroutine.

NAME:

**setdac()** ( C callable ) Set a range of digital-to-analog converters.

CALL:

```
int error, first dac, last dac;  
float dac data pointer;  
int setdac( first dac, last dac, & dac data pointer )
```

DESCRIPTION:

This subroutine sets a range of digital-to-analog converters. The +/- 1.0 unit output range is scaled to +/- 10.0 volts so a single unit is worth .0049 volts. The arguments are:

```
first dac    (int)    First converter to be set (numbering starts from  
                      zero.)  
  
last_dac     (int)    Last converter to be set (maximum is 7.)  
  
&dac_data_pointer (*) Starting location DAC data. Data are floating point  
                      values with a range of +/- 1.0.
```

RETURNS:

```
error = 0    Indicates valid transfer.  
error == -1  Indicates bad range.  
error > 0    Indicates "error" number of data words out of range.
```

USES:

Nothing.

LIBRARY:

None.

SOURCE:

/usr/csc/ele/setdac\_c.c

Analog I/O system subroutine.

NAME:

`getadc()` ( Fortran callable ) Sample a range of analog-to-digital converters.

CALL:

integer error, getadc  
error = getadc(first\_adc, last\_adc, adc\_data\_array)

DESCRIPTION:

This subroutine samples a range of analog-to-digital converters. The +/- 10.0 volt input range is scaled to +/- 1.0 units so a single bit is worth .00049 units. The arguments are:

first\_adc (integer) First converter to be sampled (numbering starts from zero.)

last\_adc (integer) Last converter to be sampled (maximum is 63.)

adc\_data\_array (real) Starting location for storing sample data. Data are floating point values with a range of +/- 1.0.

RETURNS:

error = 0 indicates valid transfer.  
error = -1 indicates bad range.

USES:

getadc\_w.j.

LIBRARY:

/lib/acrl\_rt\_lib\_f.j

SOURCE:

/usr/csc/ele/getadc\_f.c

Analog I/O system subroutine.

**setdac()** ( Fortran callable ) Set a range of digital-to-analog converters.

**CALL:**

```
integer error, setdac
error = setdac( first_dac, last_dac, dac_data_array )
```

**DESCRIPTION:**

This subroutine sets a range of digital-to-analog converters. The +/- 1.0 unit output range is scaled to +/- 10.0 volts so a single unit is worth .0049 volts. The arguments are:

**first\_dac** (integer) First converter to be set (numbering starts from zero.)

**last\_dac** (integer) Last converter to be set (maximum is 7.)

**dac\_data\_array** (real) Starting location DAC data. Data are floating point values with a range of +/- 1.0.

**RETURNS:**

**error = 0** Indicates valid transfer.

**error = -1** Indicates bad range.

**error > 0** Indicates "error" number of data words out of range.

**USES:**

setdac\_w.j

**LIBRARY:**

/lib/acrl\_rt\_lib\_f.j

**SOURCE:**

/usr/csc/ele/setdac\_f.c

Analog I/O system subroutine.

NAME:

**motsub()** ( Fortran callable ) Send scaled voltages to the 8751  
micro-controllers which in turn set  
individual DACs.

CALL:

integer torque  
call motsub ( torque )

DESCRIPTION:

This subroutine sends the motor torque command data to the 8751 micro-controller boards which in turn load the data into the digital-to-analog converters.

torque(6) (integer) Array of dimension 6 which contains the scaled data to be output on the 8751 DAC's. The range of the data is +2047 for +9.9951 volt output to -2048 for -10.0000 volt output.

REQUIRES:

Call to motint.

RETURNS:

Nothing.

USES:

motsub\_w.j

LIBRARY:

/lib/acrl\_rt\_lib\_f.j

SOURCE:

/jpw/8751COM/torsub.c

Analog I/O system subroutine.

NAME:        `finish()` ( Fortran callable )    Close serial ports to 8751s.

CALL:        `finish()`

DESCRIPTION:

This subroutine closes the serial communication lines to the 8751s. There are no arguments.

RETURNS:     Nothing.

USES:        `finish_w.j`.

LIBRARY:     `/lib/acrl_rt_lib_f.j`

SOURCE:     `/jpw/8751COM/torsub.c`



## Analog I/O system subroutines.

### NAME:

**thrust**      ( Fortran callable )    Set the discrete ports to activate the thrusters.

### CALL:

integer\*2 thrust = thrust ( x,y )

### DESCRIPTION:

This subroutine sets the states of the four discrete outputs on the Parallel Interface/Timer. It was designed for the thrusters on the SCOLE facility. The arguments can have one of three values: 1, 0, or -1 corresponding to positive, none, and negative thrust respectively.

The arguments are:

x      (integer)    State of x thruster.

y      (integer)    State of y thruster.

### REQUIRES:

Nothing.

### RETURNS:

Nothing.

### USES:

thrust\_w.j

### LIBRARY:

/lib/acrl\_rt\_lib.f.

### SOURCE:

/jpw/TIMER/pitdsc.j

Analog I/O system subroutine.

NAME:            **rtime()**        (fortran callable)    Mark the start of the real-time loop and  
change the sample time interval if required.

CALL:           call rtime(tau,flag,k)

DESCRIPTION:

An internal memory mapped timer is used to control the timing of real-time operations in the Charles River Computer. The programmable clock is required to generate a start pulse and a stop pulse for each sampling interval of the control process. The maximum interval is eighty-five seconds and the minimum interval is 5 micro-seconds. The timer is a Motorola M68230 Parallel Interfac Timer (PI/T) which provides versatile double buffered parallel interfaces and 24-bit programmable timer for M68000 systems.

Note: The call to rtime() should be made just inside the real time loop. The arguments are:

tau (real) is the sample period,  
flag (logical) is the indicator to either maintain the same value of tau or pass in a new value,  
k (integer) is the timeout parameter. If k is returned from rtime containing a 1, this indicates a normal return. If k is returned a 0, a timeout has occurred, and appropriate action should be taken. The user must supply his/her own timeout procedure.

REQUIRES:  
Nothing.

RETURNS:  
k

LIBRARY:  
/lib/acrl\_rt\_lib\_f.j  
Add " /jpw/rtime.obj " to FORTRAN compile command.

USES:  
tmset()  
init()  
rtwate()  
cktim()  
pint\_w.j

SOURCE:  
/jpw/TIMER/pint.c  
/jpw/TIMER/pint\_w.m  
/jpw/rtime.for

## REFERENCES

1. Taylor, L. W., Jr., and Balakrishnan, A. V.: A Laboratory Experiment Used To Evaluate Control Laws for Flexible Spacecraft...NASA/IEEE Design Challenge, June 1983, pp.1-2.

TABLE I. SENSOR PARAMETERS FOR CONTROL SYSTEM DESIGN

Component No.	Type	Sensed Variable	Signal Source	X Coord. (inches)	Y Coord. (inches)	Z Coord. (inches)	Sensitivity	Error	Range	Bias
1	Rate Gyro 1	s roll s pitch s yaw	ADC 0 ADC 1 ADC 2	27.8 " "	0.0 " "	-5.3 " "	0.0393 units/s <sup>-1</sup> 0.2351 units/s <sup>-1</sup> 0.2354 units/s <sup>-1</sup>	.58 deg/s rms 0.55 deg/s rms 0.53 deg/s rms	+/-360 (deg/s) +/-60 (deg/s) +/-60 (deg/s)	2.458 v 2.361 v 2.564 v
2	Rate Gyro 2	r roll r pitch r yaw	ADC 3 ADC 4 ADC 5	0.0 " "	0.0 " "	-129.3 " "	0.0395 units/s <sup>-1</sup> 0.2300 units/s <sup>-1</sup> 0.2300 units/s <sup>-1</sup>	0.43 deg/s rms 0.10 deg/s rms 0.12 deg/s rms	+/-360 (deg/s) +/-60 (deg/s) +/-60 (deg/s)	2.457 v 2.703 v 2.779 v
3	Accelerom.	sx	ADC 6	9.0	0.0	-4.5	0.1 units/g	0.17 ZF.S.	+/-20 g	0.00108 v
4	Accelerom.	sy	ADC 7	0.0	-11.5	-4.5	0.1 units/g	0.17 ZF.S.	+/-20 g	0.00066 v
5	Accelerom.	sz	ADC 8	-6.3	0.0	-4.5	0.1 units/g	0.17 ZF.S.	+/-20 g	0.00145 v
6	Accelerom.	m1x	ADC 9	-1.3	0.0	-41.0	0.1 units g	0.17 ZF.S.	+/-20 g	0.00065 v
7	Accelerom.	m1y	ADC 10	0.0	-1.3	-41.0	0.1 units g	0.17 ZF.S.	+/-20 g	0.00050 v
8	Accelerom.	m2x	ADC 11	-1.3	0.0	-87.8	0.1 units g	0.17 ZF.S.	+/-20 g	0.00001 v
9	Accelerom.	m2y	ADC 12	0.0	-1.3	-87.8	0.1 units g	0.17 ZF.S.	+/-20 g	0.00077 v
10	Accelerom.	rx	ADC 13	10.00	20.8	-129.3	0.1 units g	0.17 ZF.S.	+/-20 g	0.00103 v
11	Accelerom.	ry	ADC 14	12.00	18.8	-129.3	0.1 units g	0.17 ZF.S.	+/-20 g	0.00049 v

1 unit = 10 volt

s = shuttle  
m1 = upper mast location  
m2 = lower mast location  
r = reflector  
F.S. = full scale  
ADC = Analog-to-digital converter channel

**TABLE II. TYPICAL THRUSTER DATA FOR SIXTY PSI NOZZLE PRESSURE.**

Peak Thrust	0.641 lb
Steady State Thrust	0.32 lb
Rise Time	0.032 seconds
Thrust Duration	24 seconds

TABLE III. ACTUATOR PARAMETERS FOR CONTROL SYSTEM DESIGN

Component No.	Type	Actuation Direction	Signal Source	X Coord. (inches)	Y Coord. (inches)	Z Coord. (inches)	Sensitivity	Noise (mv rms)	Range	Bias
12	CMG (for.)	s roll s pitch	tty5 tty5	35.3 "	0.0 "	4.8 "	0.3448 (units/ft-lb) 0.3448 (units/ft-lb)	- -	+/- 1.5 ft-lb +/- 1.5 ft-lb	0 0
13	CMG (aft)	s pitch s yaw	tty5 tty5	-32.9 "	0.0 "	8.8 "	0.3448 (units/ft-lb) 0.3448 (units/ft-lb)	- -	+/- 1.5 ft-lb +/- 1.5 ft-lb	0 0
14	Thrusters	rx -rx ry -ry	DISC 1 DISC 2 DISC 3 DISC 4	12.5 " " "	21.0 " " "	-124.3 " " "	.35 lbs on/off .35 lbs on/off .35 lbs on/off .35 lbs on/off	0.0252 lb rms 0.0252 lb rms 0.0252 lb rms 0.0252 lb rms	0.35 lb avg 0.35 lb avg 0.35 lb avg 0.35 lb avg	0 0 0 0
15	Reaction Wheel	rx ry rz	DAC 0 DAC 1 DAC 2	0.0 -6.0 -4.5	-6.0 0.0 -4.5	-125.8 -125.8 -125.8	not available not available not available	- - -	not available not available not available	0 0 0
16	Reaction Wheel	m1X	DAC 3	4.0	0.0	-41.0	0.05 units/oz-in	-	+20 oz-in	0
17	Reaction Wheel	m1Y	DAC 4	0.0	4.0	-41.0	0.05 units/oz-in	-	+20 oz-in	0
18	Reaction Wheel	m2X	DAC 5	4.0	0.0	-87.8	0.05 units/oz-in	-	+20 oz-in	0
19	Reaction Wheel	m2Y	DAC 6	0.0	4.0	-87.8	0.05 units/oz-in	-	+20 oz-in	0

1 unit = 10 volt

s = shuttle

m1 = upper mast location

m2 = lower mast location

r = reflector

F.S. = full scale

DAC = Digital-to-analog converter channel

DISC = Discrete output channel

TABLE IV. SCOLE APPARATUS MASS PROPERTIES AND COMPONENT LOCATIONS

Component No.	Component Type	X Coord. (in.)	Y Coord. (in.)	Z Coord. (in.)	Weight (lb.)	Moment X (lb. inches)	Moment Y (lb. inches)	Moment YZ	I XX (slugs * in. 2)	I YY (slugs * in. 2)	I ZZ (slugs * in. 2)	I xy (slugs * inches 2)	I xz (slugs * inches 2)	I yz (slugs * inches 2)
	Sensor													
1	Rate gyro s	27.8	0.0	-5.3	1.69	46.9	0.0	-8.9	1.4	41.9	40.4	0.0	7.7	0.0
2	Rate gyro r	0.0	0.0	-129.3	1.69	0.0	0.0	-218.5	877.5	877.5	0.0	0.0	0.0	0.0
3	Accelerometer sx	9.0	0.0	-4.5	0.17	1.5	0.0	-0.8	0.1	0.5	0.4	0.0	0.2	0.0
4	Accelerometer sy	0.0	-11.5	-4.5	0.17	0.0	-0.2	-0.8	0.8	0.1	0.7	0.0	0.0	-0.3
5	Accelerometer sz	-6.3	0.0	-4.5	0.17	-1.1	0.0	-0.8	0.1	0.3	0.2	0.0	-0.2	0.0
6	Accelerometer mix	-1.3	0.0	-41.0	0.17	-0.2	0.0	-7.0	8.9	8.9	0.0	0.0	-0.3	0.0
7	Accelerometer mly	0.0	-1.3	-41.0	0.17	0.0	-0.2	-7.0	8.9	8.9	0.0	0.0	0.0	-0.3
8	Accelerometer m2x	-1.3	0.0	-87.8	0.17	-0.2	0.0	-14.9	40.7	40.7	0.0	0.0	-0.6	0.0
9	Accelerometer m2y	0.0	-1.3	-87.8	0.17	0.0	-0.2	-14.9	40.7	40.7	0.0	0.0	0.0	-0.6
10	Accelerometer rx	10.0	20.8	-129.3	0.17	1.7	3.5	-22.0	90.5	88.8	2.8	-1.1	6.9	14.3
11	Accelerometer ry	12.0	18.8	-129.3	0.17	2.0	3.2	-22.0	90.1	89.0	2.6	-1.2	8.2	12.9

TABLE IV. SCALE APPARATUS MASS PROPERTIES AND COMPONENT LOCATIONS (CONT'D)

Component No.	Component Type	X Coord. (in.)	Y Coord. (in.)	Z Coord. (in.)	Weight (lb.)	Moment X (lb. inches)	Moment Y (lb. inches)	Moment Z	I XX (slugs * in. 2)	I YY (slugs * in. 2)	I ZZ (in. 2)	I xy (slugs * inches 2)	I xz (slugs * inches 2)	I yz
	<u>Actuators</u>													
12	CMG (for.)	35.3	0.0	4.8	34.27	1208.0	0.0	162.8	24.0	1346.5	1322.4	0.0	-179.3	0.0
13	CMG (aft)	-32.9	0.0	8.8	34.27	-1127.5	0.0	299.9	81.5	1233.5	1152.0	0.0	308.3	0.0
14	Thrusters	12.0	20.8	-124.3	1.00	12.0	20.8	-124.3	493.3	484.3	17.9	-7.8	46.6	80.8
15	Reaction Wheel X	0.0	-6.0	-125.8	4.28	0.0	-25.7	-538.4	2108.3	2103.5	4.8	0.0	0.0	-101.0
16	Reaction Wheel Y	6.0	0.0	-125.8	4.28	-25.7	0.0	-538.4	2103.5	2108.3	4.8	0.0	-101.0	0.0
17	Reaction Wheel Z	-4.5	-4.5	-125.8	4.28	-19.3	-19.3	-538.4	2106.2	2106.2	5.4	-2.7	-75.7	-75.7
18	Reaction Wheel 1X	4.0	0.0	-41.0	1.45	5.8	0.0	-59.4	75.7	76.4	0.7	0.0	7.4	0.0
19	Reaction Wheel 2X	4.0	0.0	-87.8	1.45	5.8	0.0	-127.3	347.1	347.9	0.7	0.0	15.9	0.0
20	Reaction Wheel 1Y	0.0	4.0	-41.0	1.45	0.0	5.8	-59.4	76.4	75.7	0.7	0.0	0.0	7.4
21	Reaction Wheel 2Y	0.0	4.0	-87.8	1.45	0.0	5.8	-127.3	347.9	347.1	0.7	0.0	0.0	15.9
22	Solenoid	4.0	7.0	-123.8	5.50	22.0	38.5	-680.9	2626.2	2620.6	11.1	-4.8	85.1	148.9
	<u>Power Supplies</u>													
23	lambda 1	-9.5	-10.3	0.0	26.00	-247.0	-267.8	0.0	85.7	72.9	158.5	-79.5	0.0	0.0
24	lambda 2	-9.5	10.3	0.0	26.00	-247.0	-267.8	0.0	85.7	72.9	158.5	79.5	0.0	0.0
25	lambda 3	-9.5	-10.3	5.5	26.00	-247.0	-267.8	143.0	110.1	97.3	158.5	-79.5	42.5	46.0
26	lambda 4	-9.5	10.3	5.5	26.00	-247.0	267.8	143.0	110.1	97.3	158.5	79.5	42.5	-46.0
27	28v	-12.3	-10.5	5.0	7.25	-89.2	-76.1	36.3	30.5	39.7	58.9	-29.3	13.9	11.9
28	variable	-11.5	10.8	5.8	30.00	-345.0	322.5	172.5	138.5	154.0	230.9	115.9	62.0	-57.9



TABLE IV. SCOLE APPARATUS MASS PROPERTIES AND COMPONENT LOCATIONS (CONT'D)

Component No.	Component Type	X Coord. (in.)	Y Coord. (in.)	Z Coord. (in.)	Height (lb.)	Moment X (lb. inches)	Moment Y (lb. inches)	Moment YZ	I XX (slugs * in. 2)	I YY (slugs * in. 2)	I ZZ (in. 2)	I XY (slugs * inches 2)	I XZ (slugs * inches 2)	I YZ (slugs * inches 2)
29	5 +/-15v	-8.5	-5.6	0.4	2.5	-19.5	-12.9	0.9	2.3	5.2	7.4	-3.4	0.2	0.2
30	6 +5v	-5.3	-10.0	10.8	4.00	-21.0	-40.0	43.2	26.9	17.9	15.8	-6.6	7.1	13.5
31	-5v	-2.3	-10.0	10.8	4.00	-9.2	-40.0	43.2	26.9	15.1	13.1	-2.9	1.5	13.5
	<u>Counter Balance</u>													
32	wing +	-10.0	18.5	10.8	79.75	-797.5	1475.4	1724.6	2005.9	1405.9	1095.3	461.1	538.9	997.0
33	wing -	-10.0	-18.5	11.8	79.75	797.5	-1475.4	1724.6	2005.9	1405.9	1095.3	-461.1	538.9	997.0
34	none	46.0	0.0	0.0	10.00	460.0	0.0	0.0	0.0	657.1	657.1	0.0	0.0	0.0
35	air tank	15.5	0.0	10.0	35.25	546.4	0.0	352.5	109.5	372.5	263.0	0.0	-170.7	0.0
36	power mount	-10.3	0.0	-2.6	19.13	-196.1	0.0	-50.3	4.1	66.5	62.4	0.0	-16.1	0.0
37	regulator	4.0	-9.3	0.3	4.00	16.0	-37.0	1.0	10.6	2.0	12.6	4.6	-0.1	0.3
38	bracket (aft.)	-26.8	0.0	6.5	13.00	-348.4	0.0	84.5	17.1	307.0	290.0	0.0	70.8	0.0
39	power amplifier	-15.5	0.0	7.5	5.98	-92.7	0.0	44.9	10.4	55.1	44.6	0.0	21.7	0.0
40	manifold bottom	0.0	0.0	-124.5	1.68	0.0	0.0	-209.2	808.7	808.7	0.0	0.0	0.0	0.0
41	manifold top	0.0	0.0	-4.3	3.19	0.0	0.0	-13.6	1.8	1.8	0.0	0.0	0.0	0.0
42	misc. 1	-7.5	-22.5	-2.5	5.00	-37.5	-112.5	-12.5	79.6	9.7	87.3	-26.4	-2.9	-8.8
43	misc. 2	42.5	0.0	-2.5	0.30	12.8	0.0	-0.8	0.1	16.9	16.8	0.0	1.0	0.0
	<u>Structure</u>													
44	shuttle	4.9	0.0	-3.4	501.73	2458.5	0.0	-1693.3	1902.8	6967.7	8510.2	0.0	259.3	0.0

TABLE IV. SCOLE APPARATUS MASS PROPERTIES AND COMPONENT LOCATIONS (CONT'D)

Component No.	Component Type	X Coord. (in.)	Y Coord. (in.)	Z Coord. (in.)	Weight (lb.)	Moment X	Moment Y (lb. inches)	Moment Z	I XX (slugs * inches <sup>2</sup> )	I YY (slugs * inches <sup>2</sup> )	I ZZ (in. 2)	I xy (slugs * inches <sup>2</sup> )	I xz (inches <sup>2</sup> )	I yz
45	mast	0.0	0.0	-64.8	4.48	0.0	0.0	-290.1	747.7	747.7	0.0	0.0	0.0	0.0
46	reflector	12.0	20.8	-125.8	4.76	57.1	99.0	-598.6	2428.2	2385.3	134.9	-384.3	-223.0	36.9
	Total				1019.0	-82.3	133.3	-790.9	22407.3	29957.2	15817.8	-349.9	1398.3	69.1

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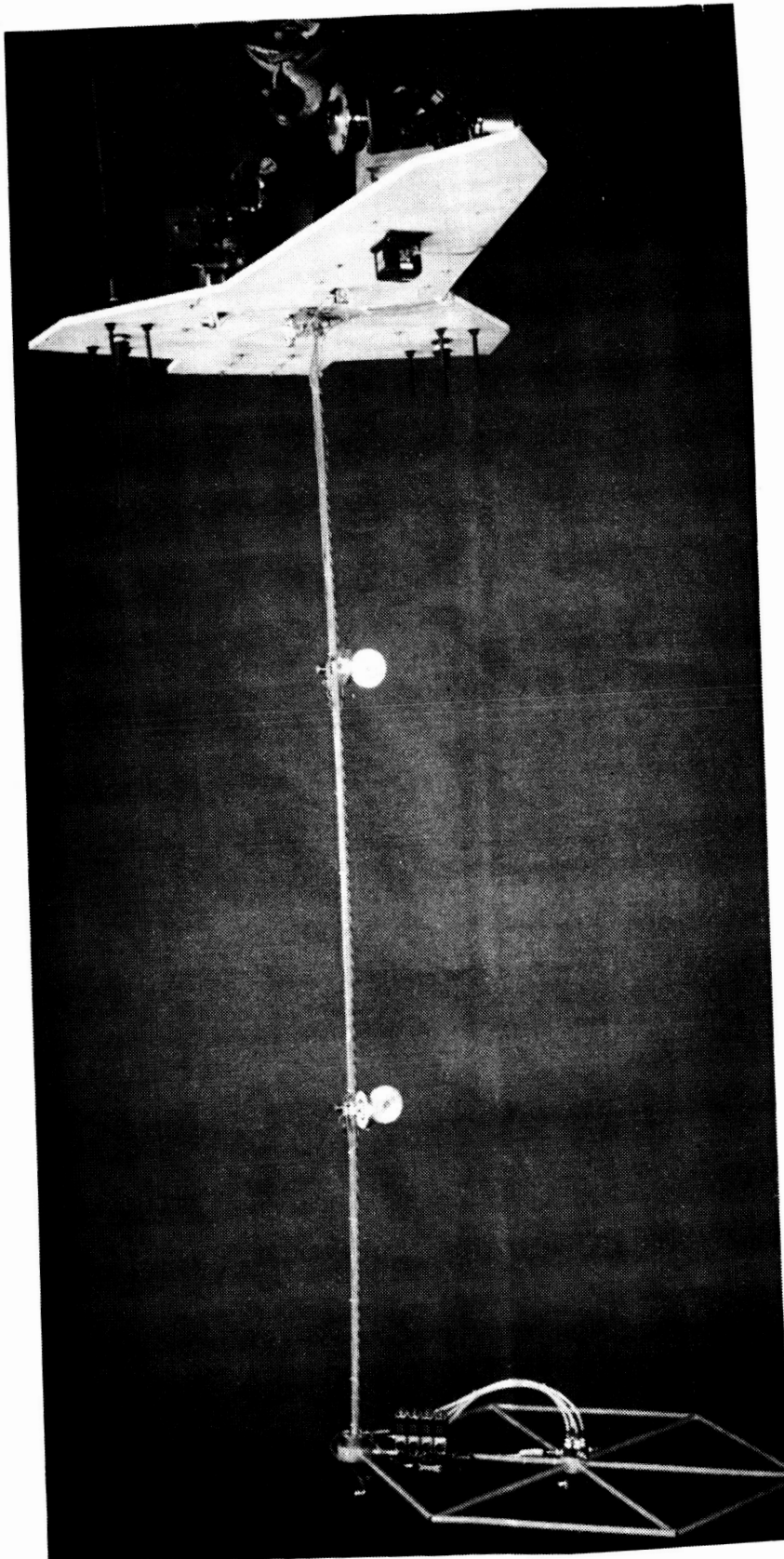


Figure 1. The SCOPE experiment apparatus.

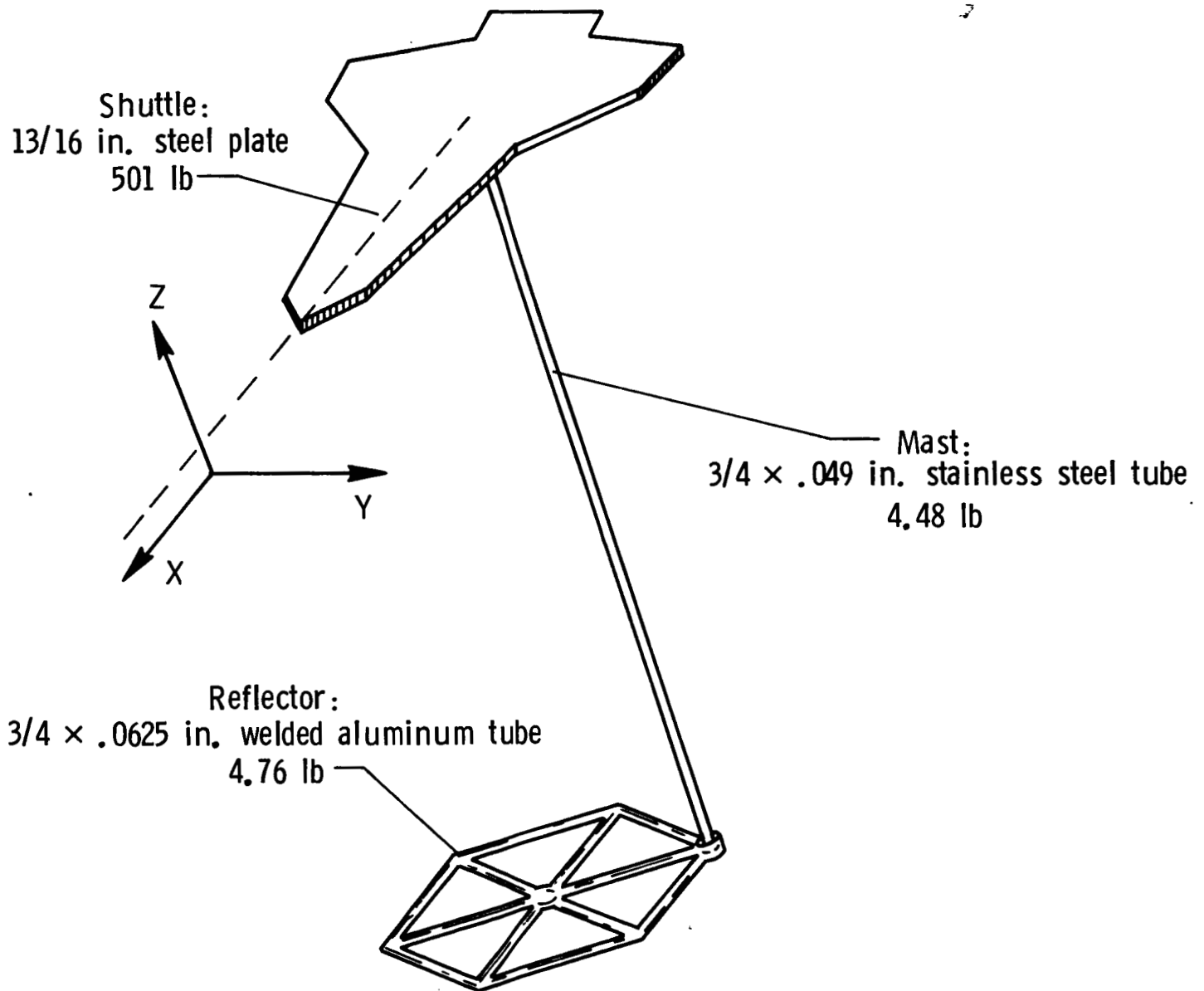


Figure 2. Basic SCOLE structural assembly.

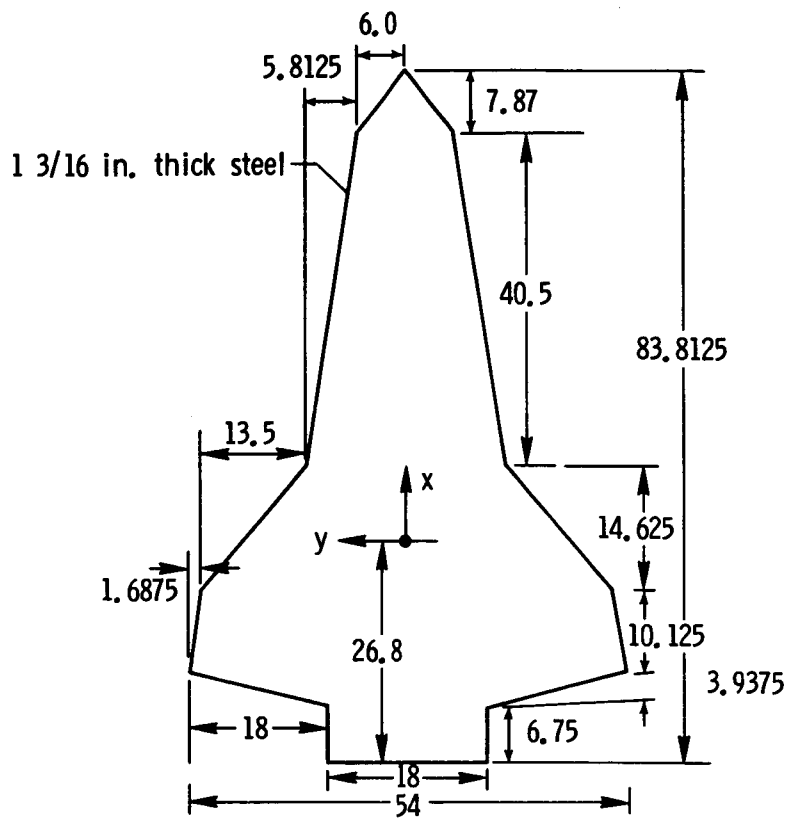


Figure 3. Shuttle planform.

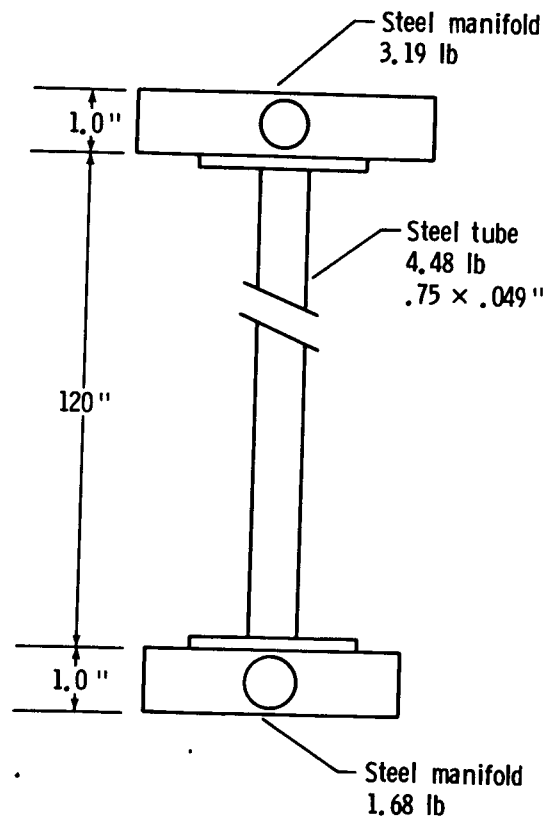
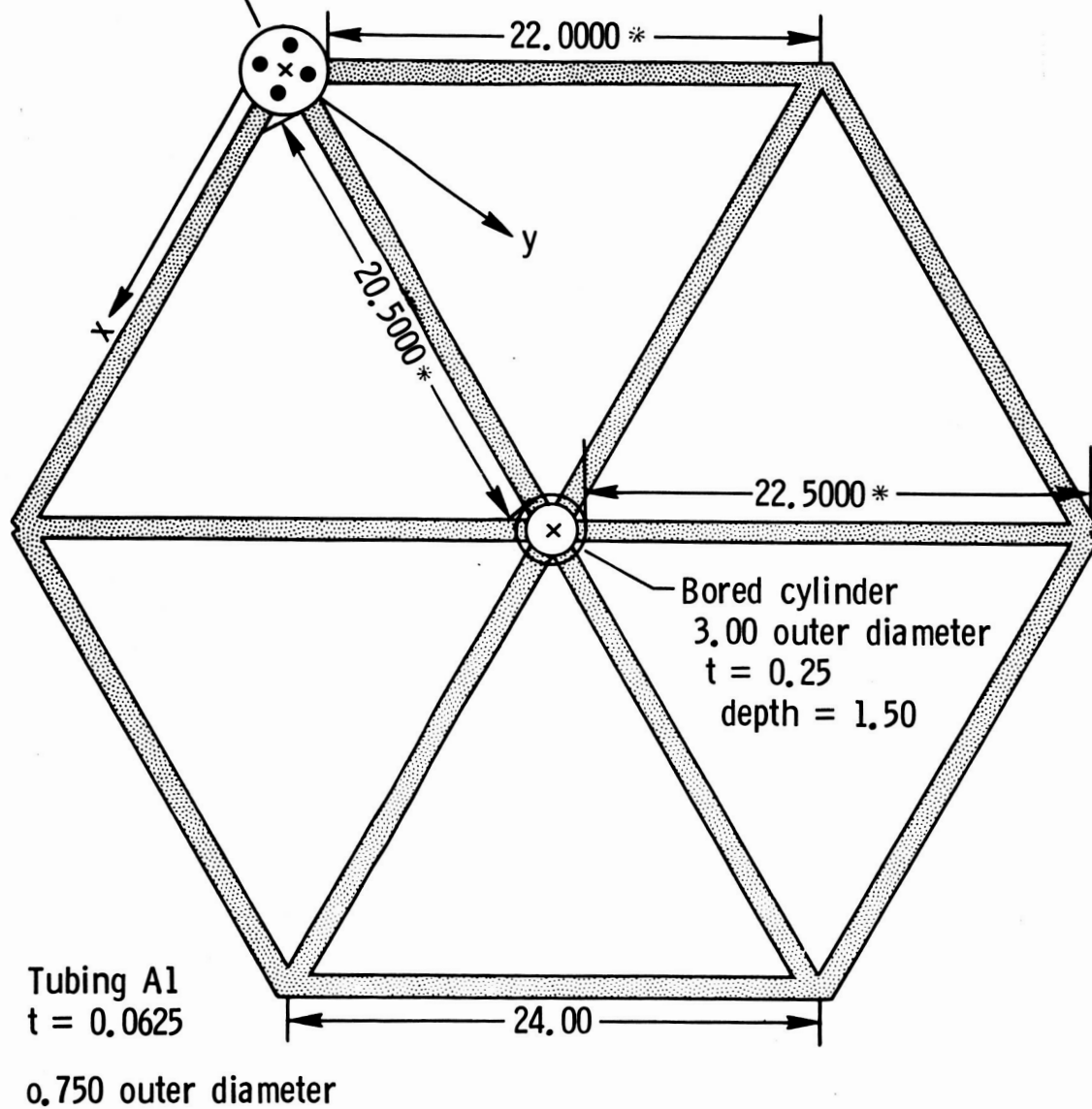


Figure 4. Mast and manifold assembly.

Bored cylinder  
 4.00 outer diameter  
 $t = 0.25$  depth = 1.50  
 Top surface  $t = 0.25$

Antenna  
 Weight 4.76 lb



All units are in inches  
 \* Length does not include length of insert.

Figure 5. Reflector assembly.

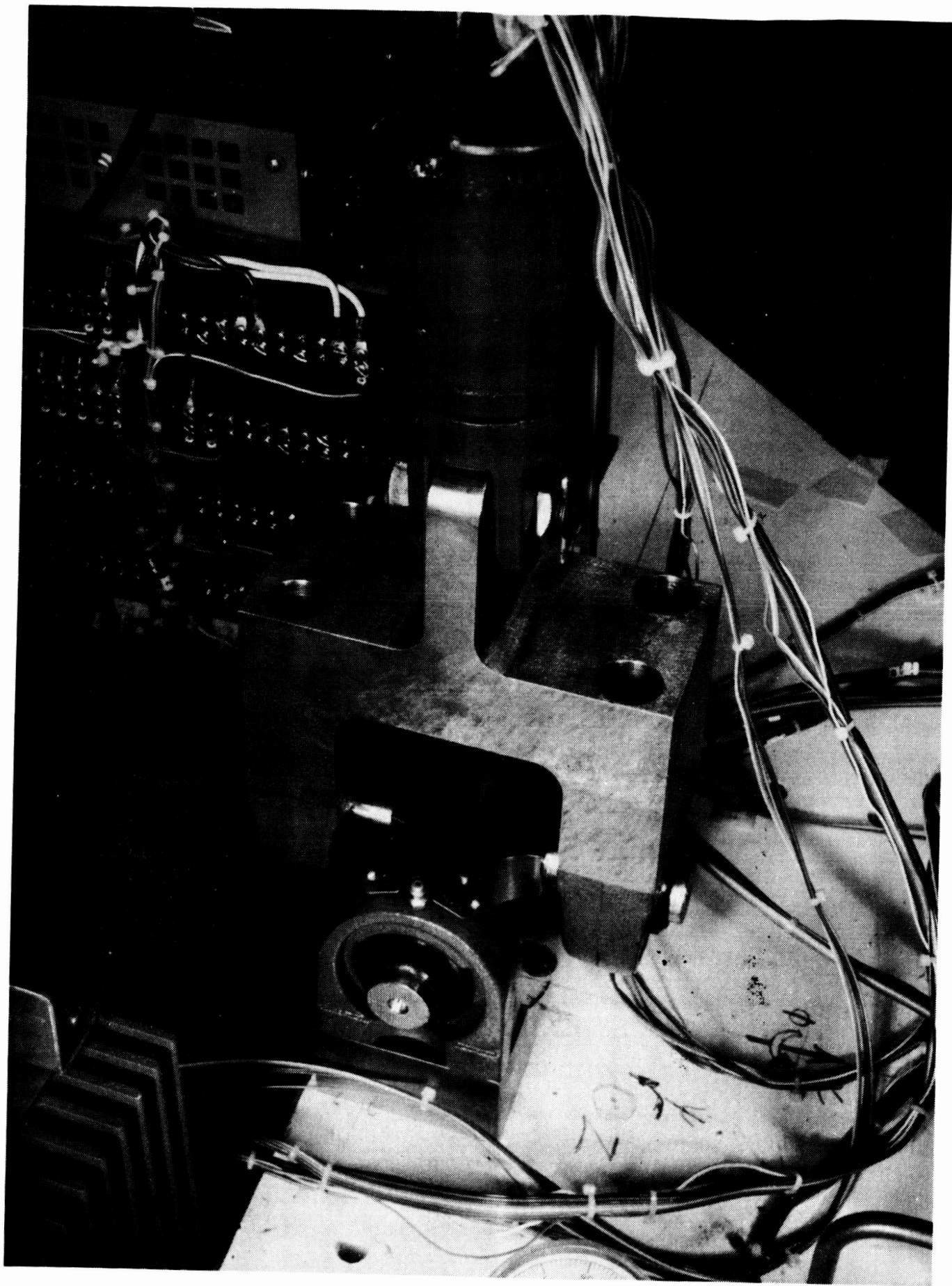


Figure 6. Universal joint suspension point.

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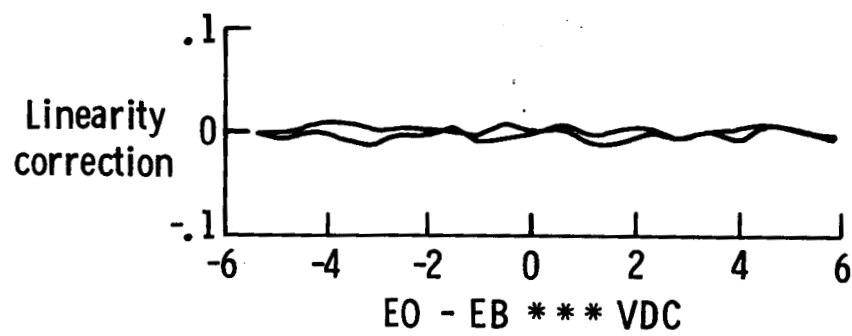
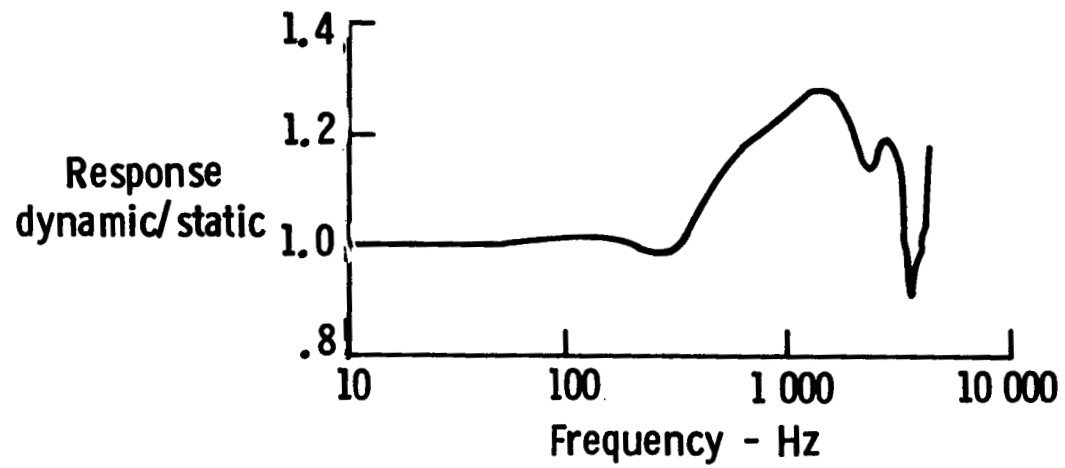


Figure 7. Typical accelerometer calibration.



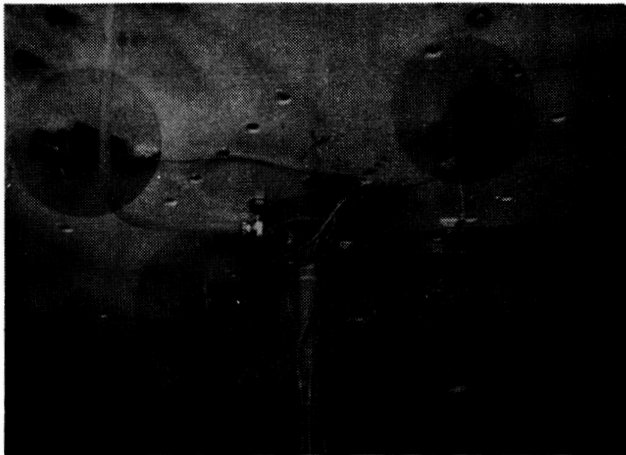


Figure 8a. Shuttle-mounted accelerometers.

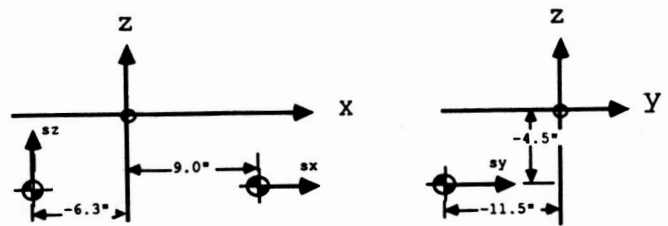


Figure 8b. Coordinates and sensing axis of  
shuttle-mounted accelerometers.

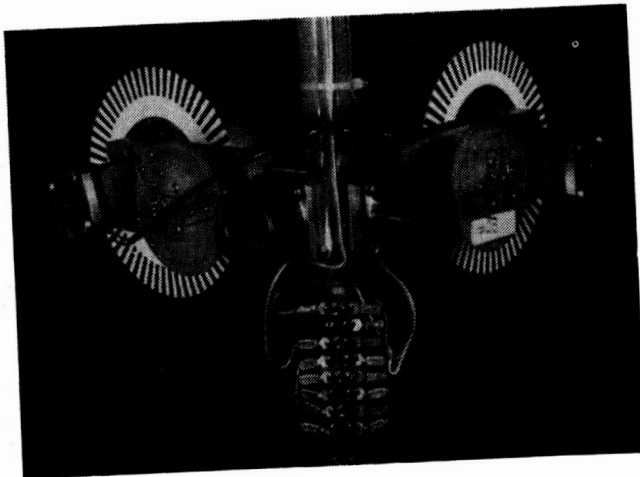


Figure 9a. Mast-mounted accelerometers.

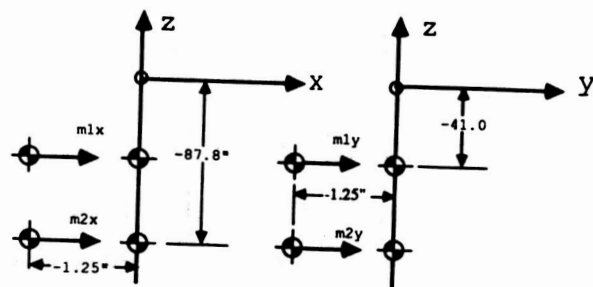


Figure 9b. Coordinates and sensing axis  
of mast-mounted accelerometers.

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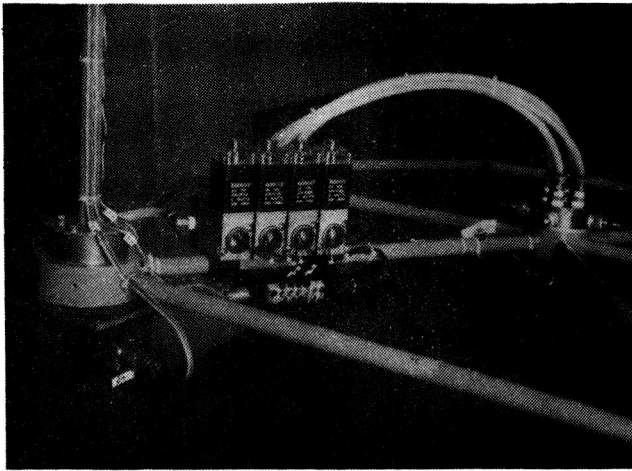


Figure 10a. Reflector-mounted accelerometers.

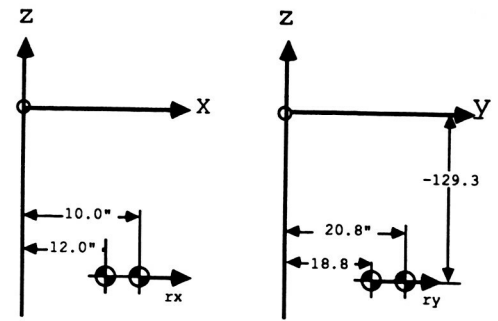


Figure 10b. Coordinates and sensing axis of  
reflector mounted accelerometers.

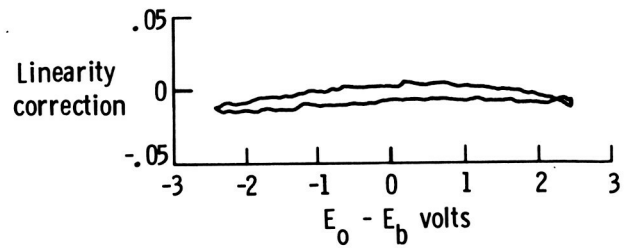
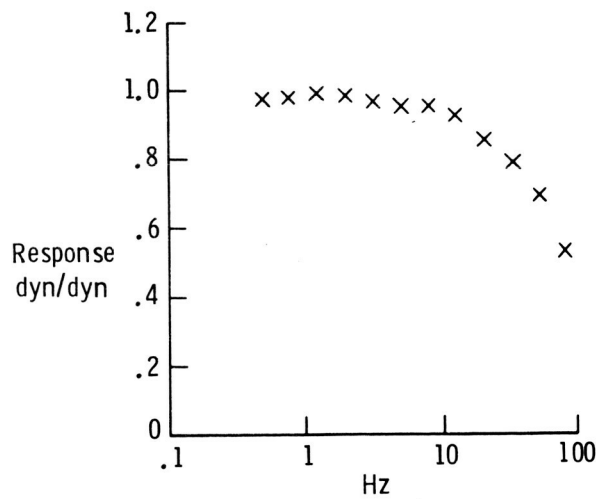


Figure 11. Typical rate sensor calibration.

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Figure 12a. Shuttle-mounted, three-axis  
rate sensor.

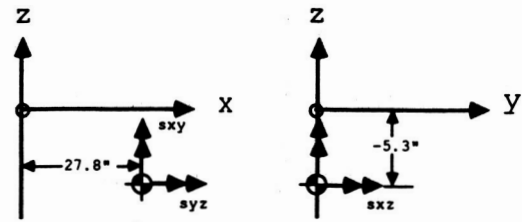


Figure 12b. Coordinates and sensing axis of  
shuttle-mounted rate sensor.

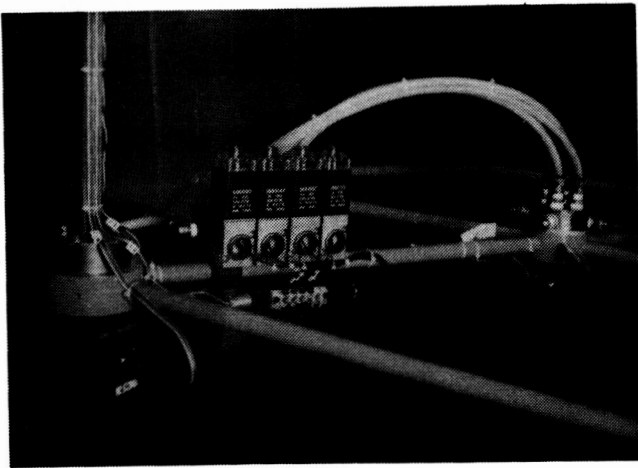


Figure 13a. Mast-end-mounted, three-axis  
rate sensor.

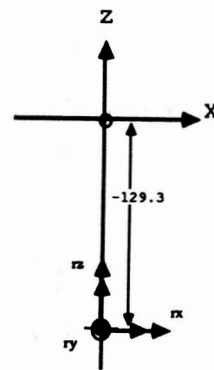


Figure 13b. Coordinates and sensing axis of  
mast-end-mounted rate sensor.

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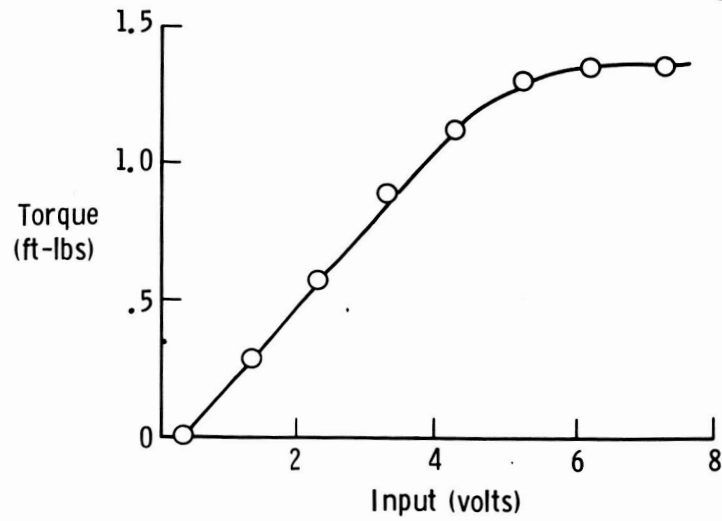


Figure 14. Typical CMG gimbal torque sensitivity curve.

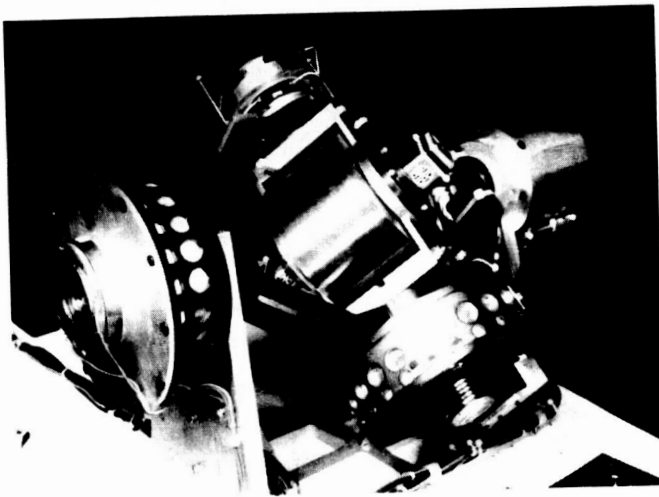


Figure 15a. Shuttle mounted forward CMG.

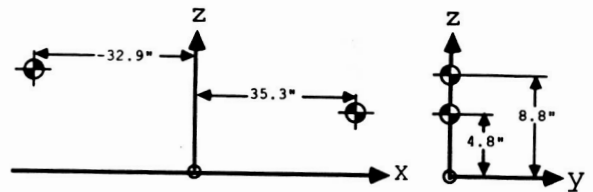


Figure 15b. Coordinates and actuation axis  
of shuttle-mounted CMG's.

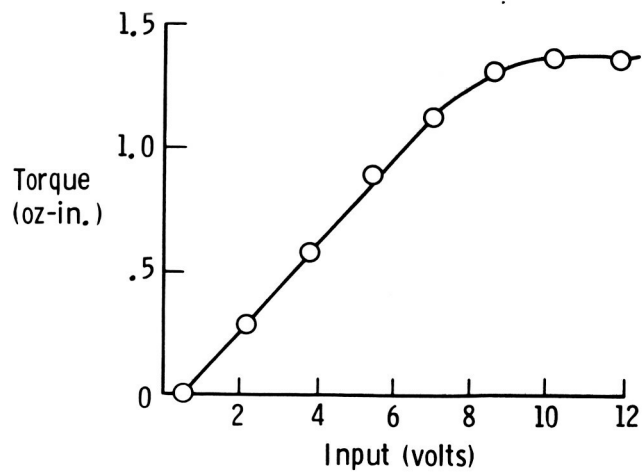


Figure 16. Typical reaction wheel torque sensitivity curve.

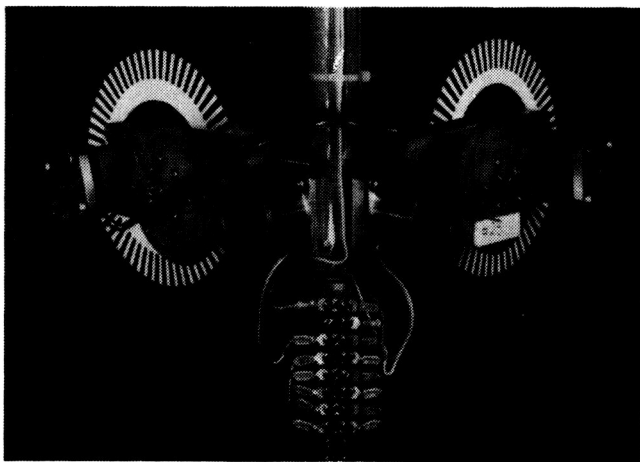


Figure 17a. Mast-mounted reaction wheels.

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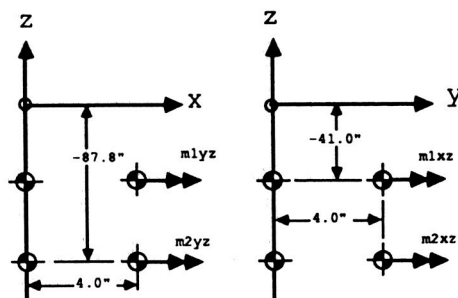


Figure 17b. Coordinates of mast-mounted  
reaction wheels.

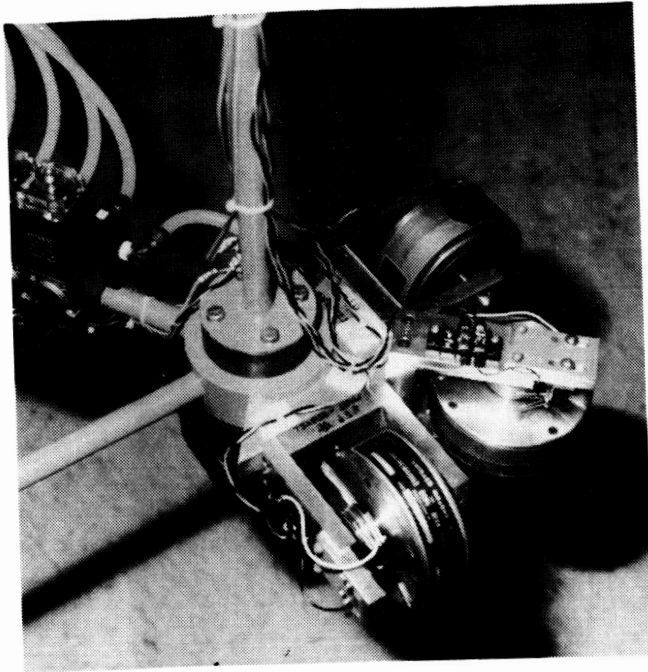


Figure 18a. Mast-end mounted reaction wheels.

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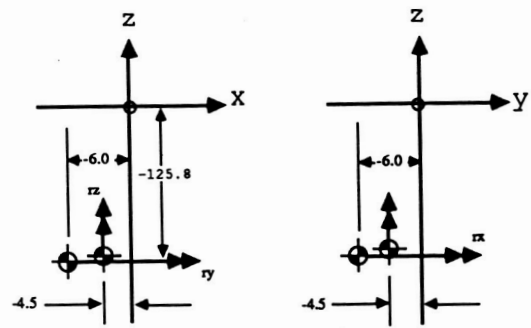


Figure 18b. Coordinate and axis of actuation  
for mast-end mounted reaction  
wheels.

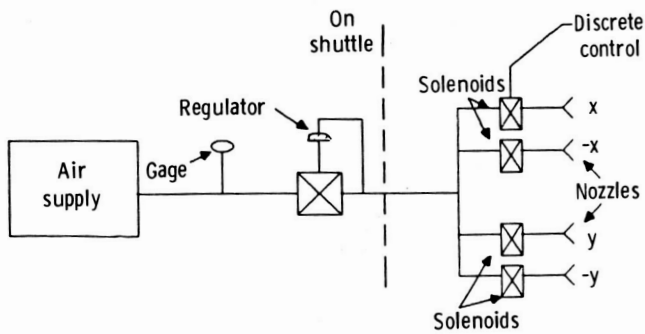


Figure 19. Thruster air supply schematic.

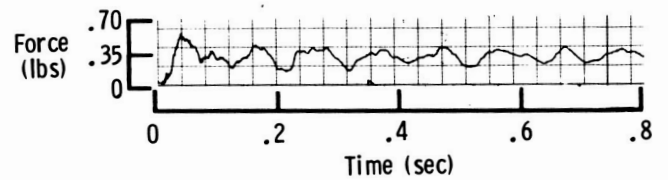


Figure 20. Thruster startup and transients.

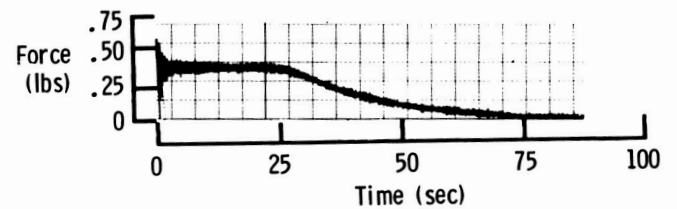
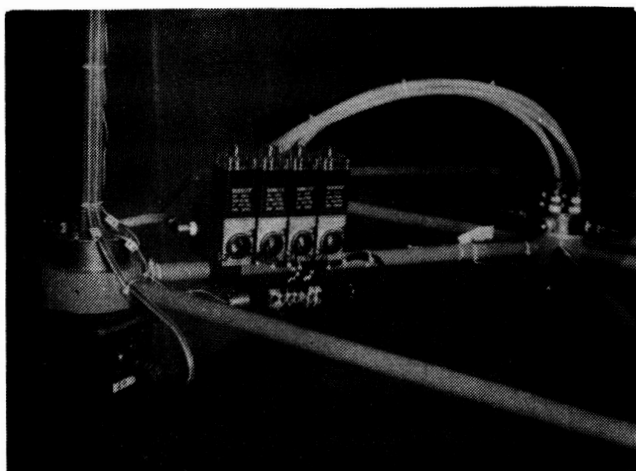


Figure 21. Thrust magnitude and duration.



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Figure 22a. Reflector-mounted thrusters.

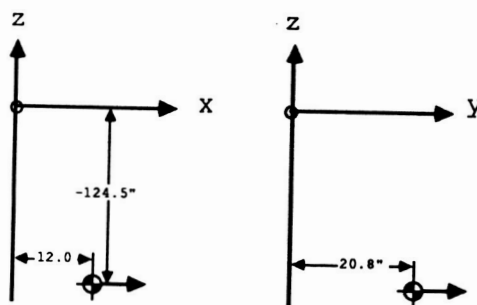


Figure 22b. Coordinates of reflector-mounted thrusters.

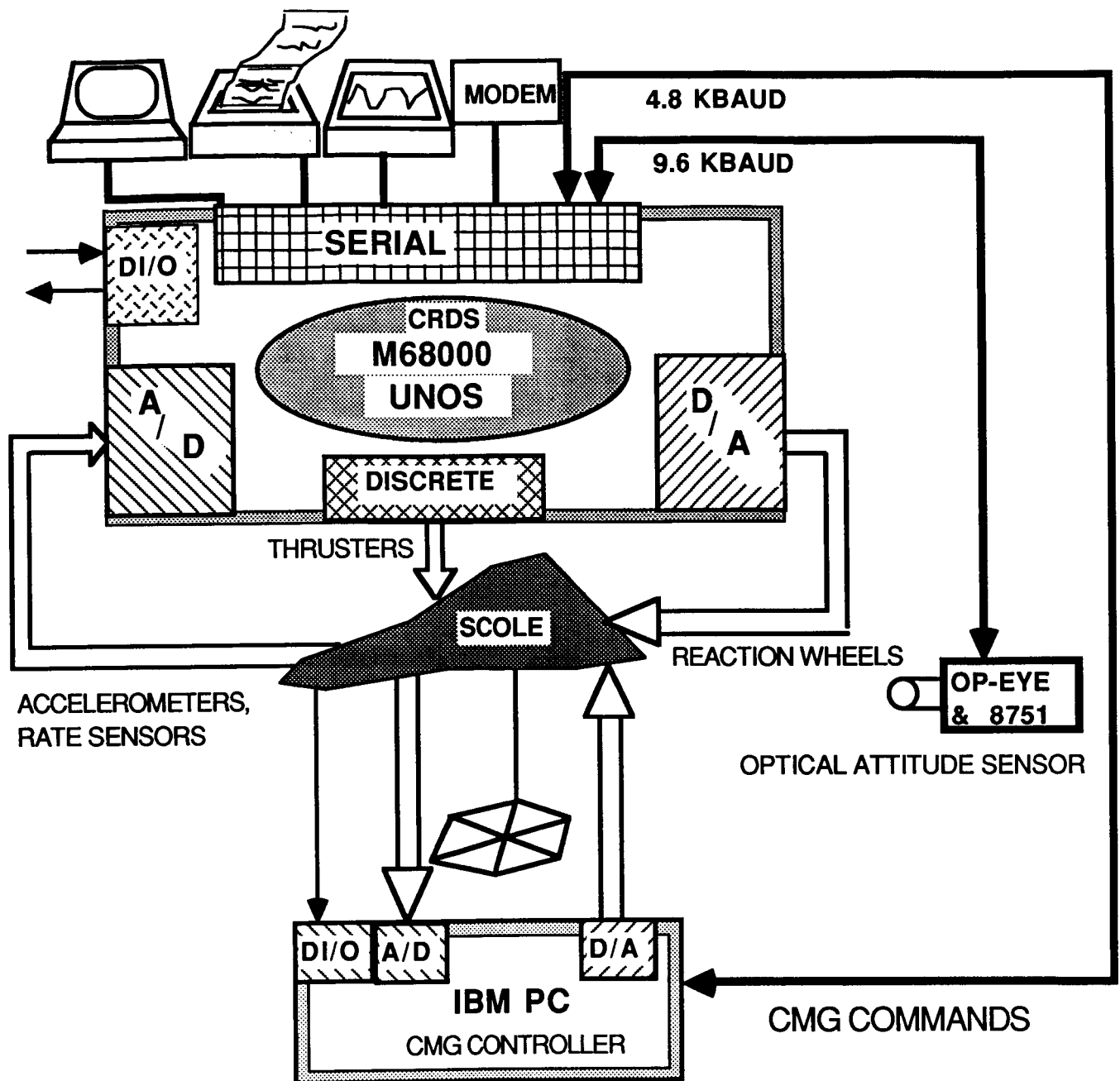


Figure 23. SCOLE computer interfaces.



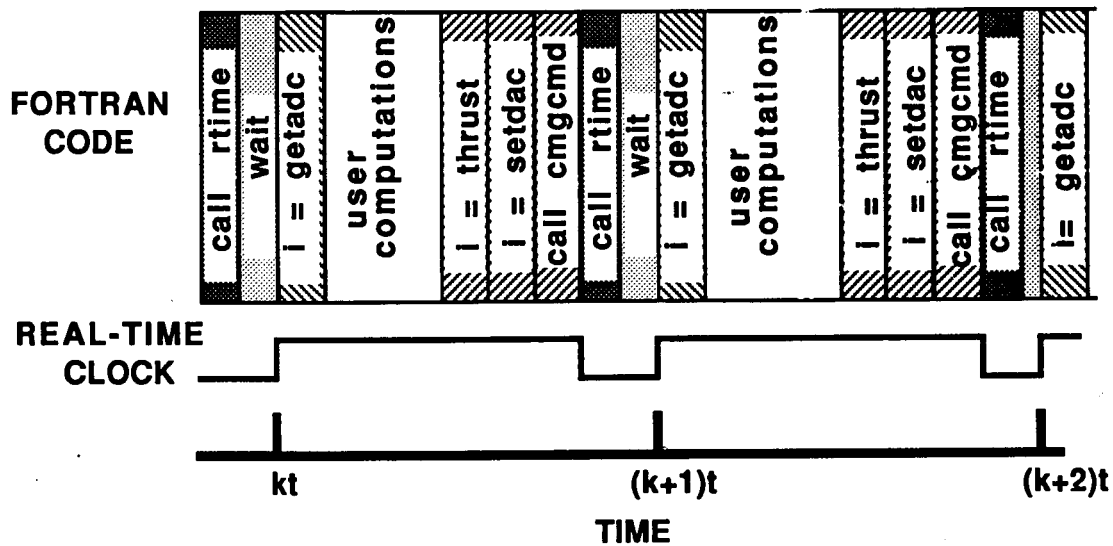


Figure 24. Real-time sample interval.

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16. Abstract  A laboratory facility for the study of control laws for large flexible spacecraft is described in the paper. The facility fulfills the requirements of the Spacecraft Control Laboratory Experiment (SCOLE) design challenge for a laboratory experiment, which will allow slew maneuvers and pointing operations. The structural apparatus is described in detail sufficient for modelling purposes. The sensor and actuator types and characteristics are described so that identification and control algorithms may be designed. The control implementation computer and real-time subroutines are also described.			
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